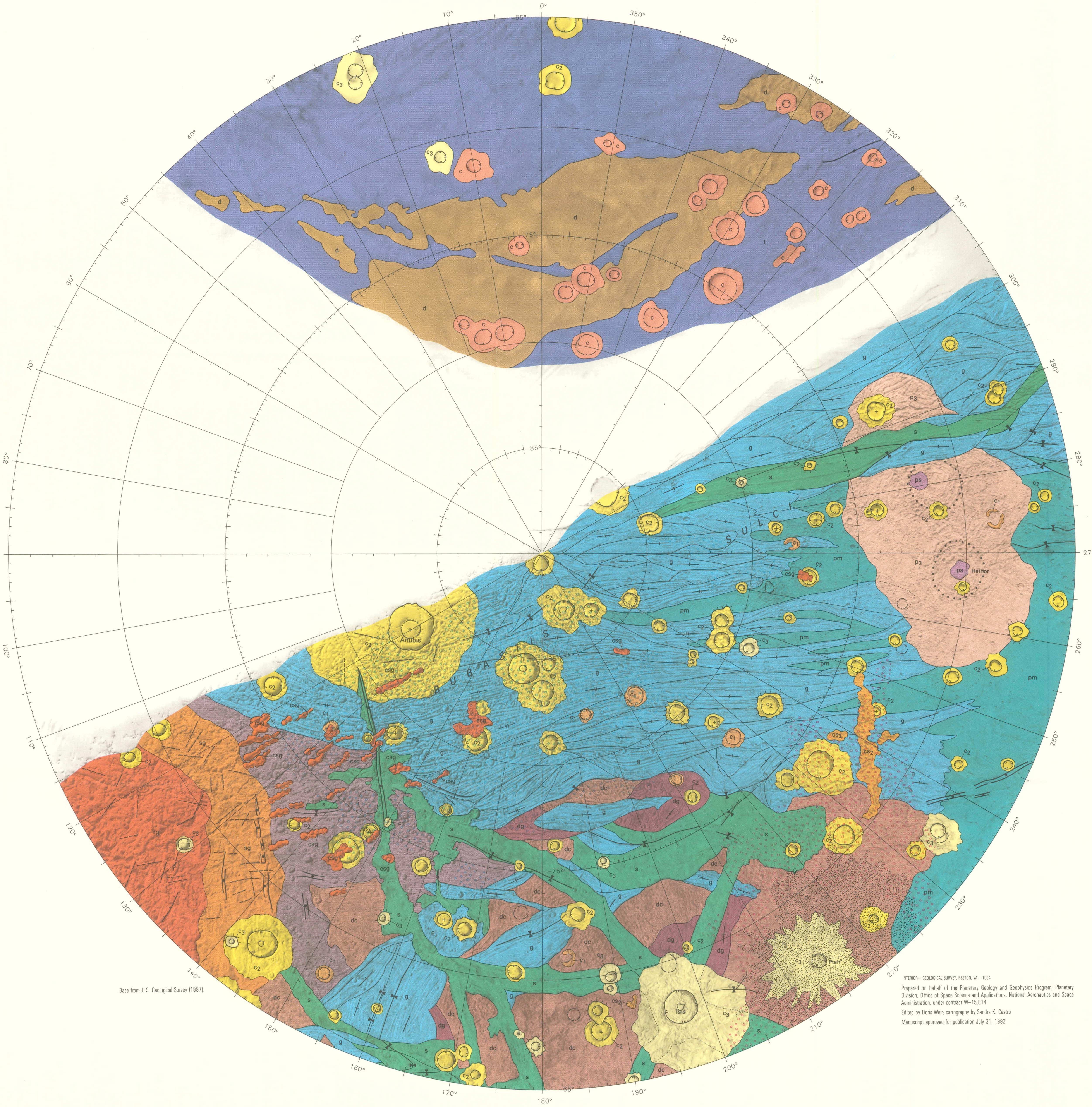
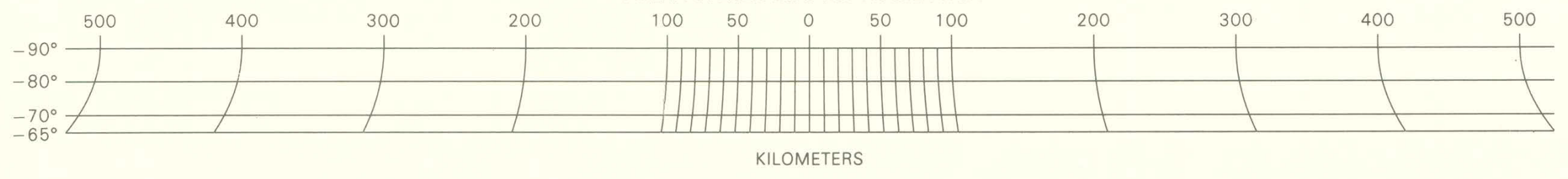
U.S. DEPARTMENT OF THE INTERIOR
U.S. GEOLOGICAL SURVEY

Prepared for the
NATIONAL AERONAUTICS AND SPACE ADMINISTRATION

ATLAS OF JOVIAN SATELLITES
1:5,000,000 GEOLOGIC SERIES
HATHOR REGION – GANYMEDE
(Jg–15) I–2388

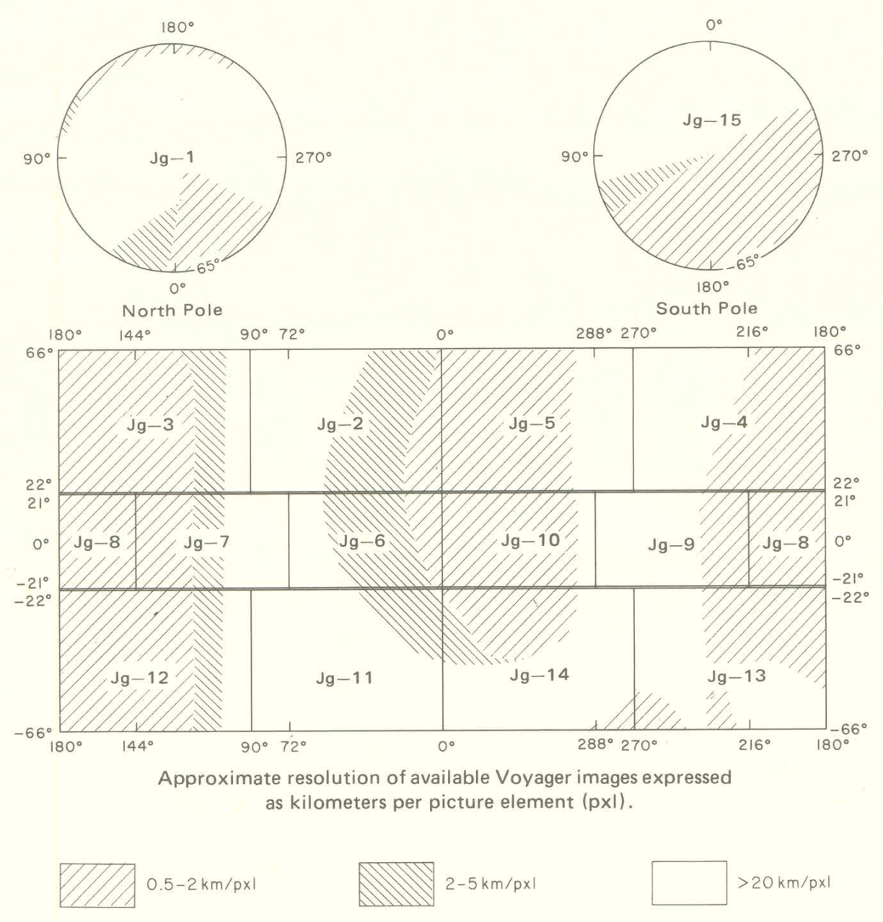


Base from U.S. Geological Survey (1987).

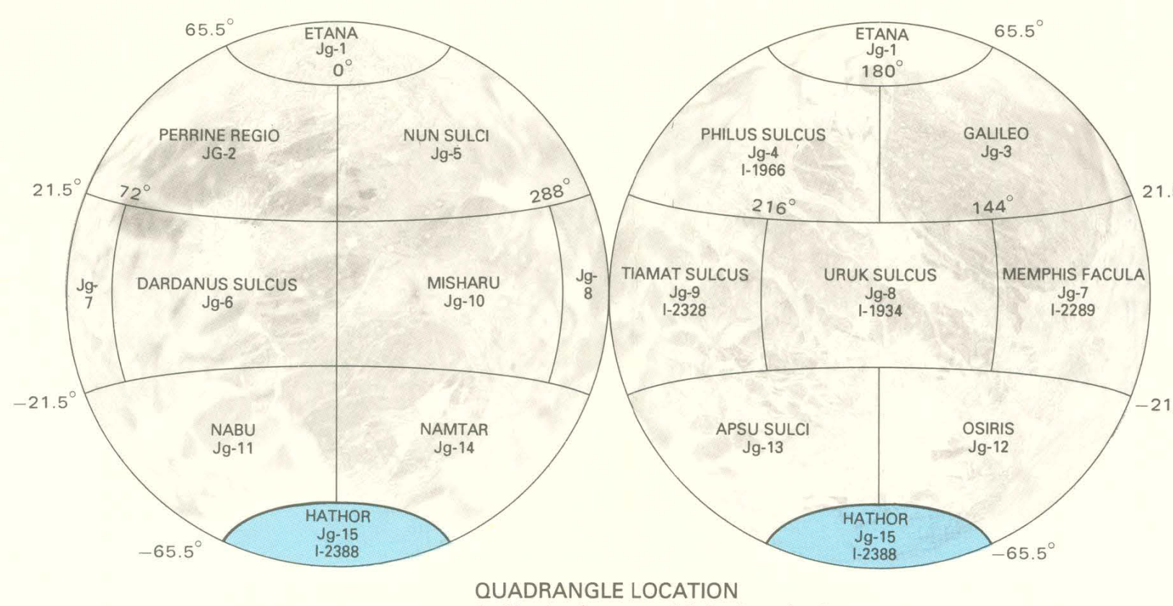


SCALE 1:5 000 000 (mm = 5 km) AT –90° LATITUDE
POLAR STEREOGRAPHIC PROJECTION

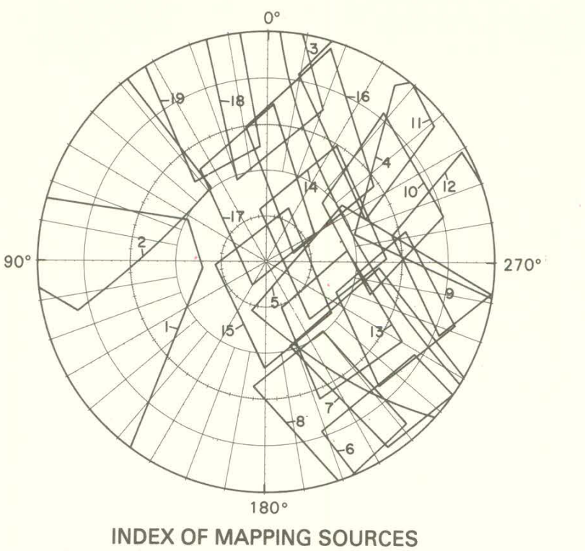
KILOMETERS



Approximate resolution of available Voyager images expressed as kilometers per picture element (pxl).



QUADRANGLE LOCATION
Number preceded by I refers to published geologic map



INDEX OF MAPPING SOURCES
The rendition of features on this map was controlled by reference to the primary source pictures outlined above. Supplemental source images used during the compilation are listed separately. Copies of various enhancements of these pictures are available from National Space Science Data Center, Code 601, Goddard Space Flight Center, Greenbelt, MD 20771.

VOYAGER 1 Primary Source Index No.	VOYAGER 1 Primary Source Picture No.	VOYAGER 2 Primary Source Index No.	VOYAGER 2 Primary Source Picture No.	VOYAGER 1 Supplemental Source Picture No.	VOYAGER 2 Supplemental Source Picture No.
1	789J1+0	3	431J2–1	318J1–2	524J2–1
2	933J1+0	4	530J2–1	1651J1–2	527J2–1
		5	533J2–1	795J1+0	536J2–1
		6	588J2–1		585J2–1
		7	592J2–1		586J2–1
		8	594J2–1		590J2–1
		9	658J2–1		664J2–1
		10	660J2–1		672J2–1
		11	662J2–1		688J2–1
		12	666J2–1		
		13	670J2–1		
		14	674J2–1		
		15	676J2–1		
		16	678J2–1		
		17	680J2–1		
		18	684J2–1		
		19	686J2–1		

INTERIOR—GEOLOGICAL SURVEY, RESTON, VA—1994

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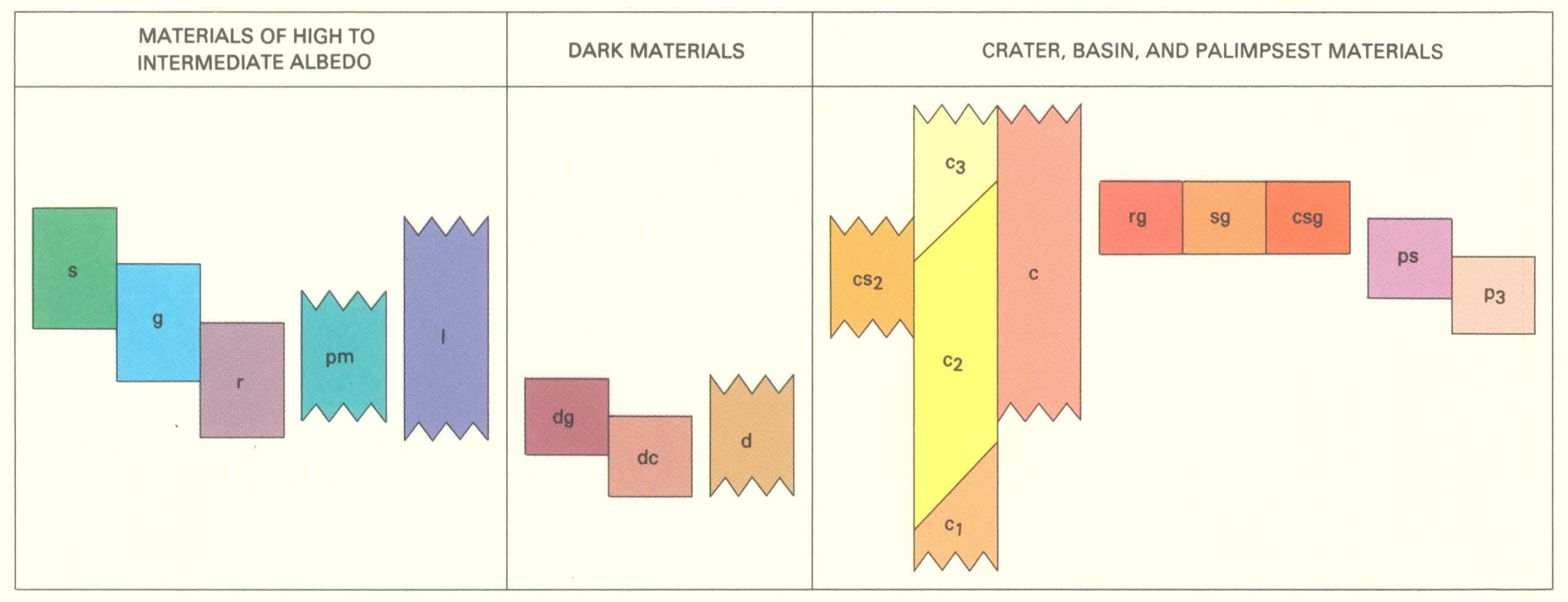
CORRELATION OF MAP UNITS



DESCRIPTION OF MAP UNITS

MATERIALS OF HIGH TO INTERMEDIATE ALBEDO

s **Smooth material**—Mostly in smooth, bright, straight to arcuate lanes. Few grooves or superposed craters. Albedo may be mottled. Typical exposure at lat 75° S., long 200° (frame 0530J2). *Interpretation:* Young plains-forming material emplaced as a fluid (water, slush, or solid ice warm enough to flow)

g **Grooved material**—Forms grooved sets and straight to arcuate grooved lanes. Groove lengths 10 to 500 km, spacing between grooves 4 to 12 km. Grooves commonly form or parallel contacts. Cut by abundant parallel or subparallel grabenlike troughs with flat or U-shaped profiles. High albedo where albedo distinctions can be made. Typical exposure at lat 67° S., long 160° (frame 0533J2). *Interpretation:* Similar to smooth material but cut by subparallel faults

r **Reticulate material**—Cut by abundant transecting grooves forming small knobs. Moderate to high albedo; moderately to heavily cratered. Typical exposure at lat 75° S., long 165° (frame 0658J2). *Interpretation:* Old grooved material refractured by multiple episodes of groove formation

pm **Mottled plains material**—Forms relatively smooth to rolling mottled plains having low to moderate crater density. Moderate albedo. Relative age uncertain. Typical exposure at lat 66° S., long 250° (frame 0662J2). *Interpretation:* Old cratered material. Apparent low crater density may be attributed, in part, to viewing conditions or topographic relaxation

l **Light materials, undivided**—Moderate- to high-albedo unit in area of low-resolution images. *Interpretation:* Materials of diverse origins and compositions, including grooved and smooth materials, plains-forming materials, and crater rays

DARK MATERIALS

dg **Grooved material**—In arcuate to irregularly shaped, grooved areas. Low albedo. Most exposures associated with or cut by light grooved material. Typical exposure at lat 71° S., long 206° (frame 0530J2). *Interpretation:* Cratered material tectonically disrupted by same forces that created light grooved material elsewhere

dc **Cratered material**—Forms dark terrain containing many small craters; grooves sparse or absent. Commonly occurs as polygons bounded by light grooved material. Typical exposure at lat 73° S., long 200° (frame 0530J2). *Interpretation:* Oldest crustal material exposed in map area, probably water ice contaminated with dark, rocky meteoritic debris. May form substantial impact-generated regolith

d **Dark materials, undivided**—Low-albedo unit in area of low-resolution images. Relief and age uncertain, but probably older than light materials

CRATER, BASIN, AND PALIMPSEST MATERIALS

[Craters assigned to three morphologic classes that reflect their degradational state and relative age. All crater, basin, and palimpsest materials thought to have formed by impact. Only craters greater than 30 km in diameter mapped except secondary craters, pedestal craters, and craters superposed on contacts between units. Basin materials mapped separately because of their significance as a time-stratigraphic datum]

Crater Materials

c_3 **Material of bright craters**—Forms bright, sharp-rimmed craters that have widespread ejecta blankets, bright ray patterns, and abundant secondaries. Superposed on all other materials

c_2 **Material of partly degraded craters**—Craters have sharp to subdued rim crests and ejecta blankets that extend less than one crater diameter from rim crest. Mostly older than smooth material in bright lanes, but generally younger than grooved materials

cs_2 **Material of secondary craters**—Forms shallow, circular to elongate craters that commonly overlap or are aligned in chains or clusters

c_1 **Material of highly degraded craters**—Forms craters with incomplete rim crests, poorly defined ejecta blankets, and no secondary craters

c **Crater materials, undivided**—Mapped where low-resolution images prevent positive age identification. Even though age uncertain, moderate to high albedo of most craters suggests young age

Gilgamesh Basin Materials

rg **Rugged material**—Hummocky or blocky material surrounding Gilgamesh inner plain. Inner facies of ejecta from Gilgamesh basin

sg **Smooth and lineated material**—Mottled, dark material that has a lineation radial to Gilgamesh or parallel to groove trends in adjacent units. Outer facies of ejecta from Gilgamesh basin

csg **Material of secondary craters**—Forms mostly irregular craters in overlapping chains surrounding Gilgamesh basin

Palimpsest Materials

ps **Smooth palimpsest material**—Makes up relatively featureless plains that have circular outlines. Low albedo relative to surrounding terrains. Typical exposure at lat 72° S., long 280° (frame 0664J2). *Interpretation:* Extruded ice, ejecta fallback, or impact melt

p_3 **Material of palimpsests having internal structures**—Forms circular structures having low, hummocky relief surrounding central plain. Palimpsest materials (units p_1 and p_2) older than mapped palimpsests not recognized in Hathor region. *Interpretation:* Impact basins that have undergone some combination of rapid (post-excavation) collapse, slow topographic relaxation, and volcanic burial

Contact—Dashed where approximately located; dotted where buried. Includes domain boundaries within grooved and smooth materials

Fault or narrow graben

Scarp—Line at top of cliff; hachures point downslope

Throughgoing, conspicuous groove—Steep infacing scarps and flat floor. Interpreted as graben

Trend of sharp groove set—Schematic

Trend of subdued groove set—Schematic

Lineament—Indistinct narrow linear depression, ridge, or break in slope

Crater rim crest—Dashed where indistinct

Crater rim crest—Highly subdued or buried

Pedestal crater—Outer edge of ejecta blanket is low scarp

+ **Peak on crater floor**—Rugged individual or compound peaks near center of craters

Peak ring on crater floor—Rugged ring of peaks near center of crater

○ **Pit on crater floor**—Within craters larger than about 20 km in diameter

Palimpsest ring

Bright ray material—Radial streaks or bright halos from bright, fresh crater. Superposed on all other materials. Visible only at high sun angle

Field of secondary craters from crater Ptah

Field of secondary craters from Gilgamesh basin

INTRODUCTION

Ganymede, the largest of Jupiter's satellites and one and a half times the size of Earth's Moon, shows evidence of surface processes that are strikingly different from those of terrestrial bodies. In contrast to the rocky crusts of the inner planets, the outer crust of Ganymede is composed of a water-ice and rock mixture with ice predominating. The surface has had a longer and more complex tectonic history than that of the Moon or Mercury and a different style of volcanism than that of the Earth, Venus, or Mars.

The global geology of Ganymede was mapped by Shoemaker and others (1982). Ganymede's surface is chiefly composed of crater materials, light materials, and dark materials (Smith and others, 1979a, b; Lucchitta, 1980; Shoemaker and others, 1982). (Light and dark are relative terms; even the dark material on Ganymede is brighter than the lunar highlands.)

The most pervasive unit in the Hathor region is light grooved material. The region also contains materials of the craters Isis and Ptah and of two palimpsests, as well as ejecta from the Gilgamesh basin (in Jg–12, centered about 150 km north of the Hathor map border).

Information for the geologic mapping of Ganymede comes from images obtained by the Voyager 1 and 2 spacecraft during their flybys through the Jovian system in 1979. Approximately 40 images of the Jg–15 region were acquired, although half of the region was either not imaged at all or imaged only at very poor resolution. Resolution and look angle are varied even over the better covered half. Resolution ranges from poor for obliquely viewed scenes to 550 m per pixel for the highest resolution frames. This resolution is the best obtained for Ganymede by Voyager (see resolution diagram). Illumination ranges from extremely low sun angles along the 300° and 120° meridians, marking the approximate location of the terminator during the Voyager 2 flyby, to about 65° elsewhere. The low sun angles result in the loss of topographic detail in shadows and the absence of albedo information; hence, correlation of units between areas of high- and low-sun-angle illumination is difficult.

Topography and morphology are difficult to discern in the poorly imaged portion of the map region. Therefore, materials here are mapped as albedo units and crater materials only. The albedo units may include any or all of the units in the better imaged portion of the region or even entirely different materials.

STRATIGRAPHY

Albedo, topography, and morphology are the characteristics used for distinguishing the mapped units. Superposition and transection relations in the map region indicate that the younger units tend to be brighter than the older units. Also, smooth units generally appear to be younger than rough units. The units (other than crater and basin materials) are divided into two major albedo groups: high to intermediate and dark. The groups are further subdivided on the basis of topography and morphology; grooved and smooth materials of varied ages are present over more than two-thirds of the better imaged half of the region.

The oldest material in Jg–15 is dark cratered material (unit dc), much of which occurs in relatively small polygons outlined by grooved lanes. Contacts with younger units are commonly abrupt structural boundaries except where overlain by young crater materials. Although old, the cratered material lacks remnants of large craters but retains abundant small, degraded craters. Presumably, large craters and basins have been destroyed by processes such as viscous relaxation, mass wasting, and resurfacing, or possibly they did not form in the first place.

Some darkening of material units with time can be attributed to a combination of magnetospheric sputtering, water-ice sublimation, and accumulation of dark, carbonaceous, meteoritic debris on a surface that is mostly water ice (Schenk and McKinnon, 1991). Albedo variations among different units may also be due to variations in the original ice-to-rock ratio of the units (Johnson and others, 1983; McKinnon and Parmentier, 1986). The stratigraphy beneath dark material is not known in this map region, but bright material excavated elsewhere on Ganymede by large impacts indicates that at depths greater than 5 km the dark material is underlain by ice less contaminated by silicates (Shoemaker and others, 1982, as discussed in McKinnon and Parmentier, 1986).

The mottled plains material (unit pm) is poorly resolved. This unit forms a rolling plain and appears to be cut by light grooved material; hence, it is older than this material. Despite its apparent age, the mottled material does not appear to have a high density of superposed craters. However, its exposures, as mapped, were viewed only obliquely and at low resolution, so the mottled material may have a more complex morphology and a higher crater density than are visible in the available images.

Three types of grooved material occur in the map region: dark grooved material (unit dg), reticulate material (unit r), and light grooved material (unit g). The dark grooved material is preserved between some younger grooved lanes and reticulate material. It is morphologically similar to, and associated with or cut by, the light grooved material. The knobby topography of the reticulate material is caused by a pattern of grooves crosscutting at high angles. The light grooved material is mapped where albedo distinctions can be made and forms curvilinear lanes and sets cut by abundant parallel to subparallel troughs. The grooves are spaced about 4 to 12 km apart (Grimm and Squyres, 1985), and within any particular set the groove spacing is very consistent. Grooves are as long as several hundred kilometers. Typical groove profiles have gentle U-shapes or flat floors; crest-to-floor depths are 300 to 400 m (Squyres, 1981). Some groove sets die out along strike, while others terminate abruptly against older sets or converge in a fanlike pattern. South of about lat 75° S., the light grooved unit is cut by many juxtaposed, densely grooved sets; farther north the spacing is less dense and grooves occur singly or in small groups.

Although mapped as a single stratigraphic unit, grooved material south of about lat 75° S. is primarily composed of contiguous lanes of locally varied ages. Within this area is a trend of increasing groove density with increasing age. The least grooved lane coincides approximately with the 285° meridian and is mapped as young smooth material (unit s) on the basis of physiography and relative age.

In bright grooved terrains elsewhere on Ganymede, dark-halo craters are evidence for the excavation of dark materials from beneath bright materials. Estimates of the thickness of bright materials in Uruk Sulcus (about lat 35° N.–10° S., long 140°–180°) range between 1.0 and 1.6 km (Schenk and McKinnon, 1985). Dark-halo craters may not be seen in the map region because of masking by polar frost or the low sun angle of the images, but the thickness of bright materials in this region is assumed to be similiar to that at Uruk Sulcus.

Smooth material forms bright lanes. This material commonly has a dark mottling, suggestive of a thin layer of bright material overlying dark material or of locally varied silicate content. The rare grooves occur singly; most are at the lane margins. Apparently this unit has been emplaced either by the filling of structural troughs (in areas where it has sharp boundaries), or by the flooding of low-lying areas (where it has a more mottled appearance and irregular or diffuse boundaries).

The smooth and grooved light materials are close to pure ice in composition (Clark and others, 1986; McKinnon and Parmentier, 1986), but their physical state during emplacement as water, slush, or ice has not yet been determined. Exposures of the smooth unit and partly flooded craters in the map region are compatible with liquid water or slush, whereas a possible flow front at lat 78.5° S., long 165.0° (frame 658J2–001) is more indicative of the solid-state flow of ice. A graben about 370 km long at lat 78° S., long 140° has been resurfaced with smooth material. Ice, slush, or water appears to have spilled over from this graben and partly buried surrounding grooved materials, especially near one graben terminus. This flooding episode is known to postdate the formation of the Gilgamesh basin, because the smooth material buries secondary craters from Gilgamesh. Apart from some impact materials, the smooth material appears to be the youngest unit in the map region.

CRATERS, BASINS, AND PALIMPSESTS

Craters and basins are conspicuous features on Ganymede as on the Moon, Mercury, and Mars. However, unlike the case on the terrestrial planets, topographic relaxation may be a major factor in altering large-crater and basin morphology on Ganymede. Crater and basin topographic expression ranges from well-defined crater forms to circular, high-albedo patches probably representing very relaxed or buried craters (Smith and others, 1979b; McKinnon and Parmentier, 1986; Lucchitta and Ferguson, 1988; Thomas and Squyres, 1990), or possibly craters with little initial relief. These circular albedo patches are called palimpsests (Passey and Shoemaker, 1982). Palimpsest-like features that retain some topographic expression of rim and other structural units (such as central pits) are termed penepalimpsests by Passey and Shoemaker (1982), but their material is here classified as palimpsest material (unit p_3). The albedo distinction favors the identification of palimpsests in regions of dark terrain, and high resolution favors the identification of penepalimpsests or basinlike palimpsests. Ancient palimpsests (units p_1 and p_2) are not recognized in this map region, which may be due to the lack of widespread dark units.

Although some medium-sized (20- to 50-km diameter) old craters can be seen in the Hathor region, no very large, old craters are preserved, probably because of the dominance of grooved and smooth materials. A relative lack of very large craters on older dark units elsewhere on Ganymede is attributed to a combination of two factors: (1) topographic relaxation, which may occur either soon after impact or over time as viscous creep; and (2) a dearth of large impactors in the Jovian projectile population compared with those responsible for the late heavy bombardment on the terrestrial planets (Strom and others, 1981; Woronow and Strom, 1982; Chapman and McKinnon, 1986).

Highly degraded craters having incomplete rims (unit c_1) are scarce. Craters that have partly degraded rims (unit c_2) are found both on materials that are older than Gilgamesh ejecta and superposed on Gilgamesh materials. Crater rim materials superposed on grooved materials are locally cut by grooves, although the interiors of the craters are mostly undisturbed. This observation suggests that some of the partly degraded craters were formed after groove formation and that the ejecta and rim deposits are following the underlying topography. Bright craters having sharp rims (unit c_3) and bright ejecta are superposed on all other materials. The crater Ptah, 26 km in diameter, appears to be the youngest crater in the region; its bright ejecta are superposed on deposits of the 77-km diameter crater Isis.

Over the whole of Ganymede, including the Hathor region, central peaks dominate in craters less than about 20 km in diameter (Greeley and others, 1982; Passey and Shoemaker, 1982). In craters larger than 20 km in diameter, such as Isis, the dominant interior structure is a central pit (Passey and Shoemaker, 1982). At still larger diameters, craters may contain inner rings. An example is Anubis, a double-ringed crater within a region of complex grooved terrain. Its outer rim is 100 km in diameter; its prominent inner ring is about 40 km in diameter and slightly off center. Although possibly a peak-ring basin as seen on the Moon, Mercury, and Mars, Anubis may be chance superposition of two impact craters or a large central-pit crater. It is highly shadowed in the available images, making a more definite interpretation difficult. Secondary craters from the Gilgamesh basin are superposed on the ejecta blanket of Anubis; thus it is older than Gilgamesh.

About 5 percent of fresh craters on Ganymede have ejecta that terminate in scarps (Horner and Greeley, 1982). These pedestal craters are more abundant in the higher resolution images of this map region than elsewhere on Ganymede, and they appear to be most common on the smooth materials. We interpret their apparent abundance here to result from a combination of their youth, the image resolution, and the material on which they are superposed: pedestal formation may be ubiquitous on Ganymede, but the pedestal scarps degrade with age, they cannot be discriminated if the resolution is too low, and they are recognizable only against smooth background material. The pedestal craters identified in this map region appear to postdate the formation of the grooved units and are thus relatively young.

A mountainous annulus of the Gilgamesh basin extends into the map region from about long 145° to the terminator at long 115°, even though the basin's 150-km-diameter central plain is centered at lat 62° S., long 124°, outside the map region. Material of the Gilgamesh basin is subdivided into two facies: an inner rugged material (unit rg) and an outer blanket of smooth and lineated material (unit sg). Although the radial lineaments are more common in the outer unit, they do cut both basin facies. The northern part of the contact of the two facies coincides with a topographic offset, basin side down, that probably consists of a low, irregular set of scarps and slopes that are probably related to basin ring formation. The nearby major scarp in the inner rugged material is an extension of the main ring of Gilgamesh, which may be structurally equivalent to the Cordilleran rim of the Orientale basin on the Moon (McKinnon and Melosh, 1980; Shoemaker and others, 1982). Secondary craters from Gilgamesh are superposed on the outer edge of the lineated materials and extend outward onto adjacent grooved materials.

Hathor and an unnamed basin (lat 72° S., long 281°) are twin palimpsests having an ill-defined, smooth central depression surrounded by an irregular annulus of subdued, short, semiconcentric ridges; the width of the annulus is approximately equal to the diameter of the central depression. The ring symbol is placed on the first hummocky ring outside the smooth inner plain. This ring is the most obvious topographic feature of each palimpsest, but it probably does not correspond to the rim crest of craters and well-defined basins. Hathor-related material appears to be superposed on older groove sets, but younger groove sets at lat 73° S., long 286° transect the palimpsest material. Because of its better preserved topography and the superposition of its secondaries, Hathor appears the younger of the two palimpsests. Both Hathor and its companion basin are much more subdued than the Gilgamesh basin, but they exhibit similar features such as a central plain and an extensive annulus of hummocky material. Smooth plains material (unit ps), darker than its surroundings, occurs on the floors of Hathor and the unnamed palimpsest and is assumed to be ejecta fallback, impact melt, or both.

STRUCTURE

The dominant structures of the region are subparallel groove sets and long, bright lanes (sulci) that are smooth to moderately grooved. The lanes sharply truncate topographic features in the older dark terrain, which suggests that bright material is in many areas tectonically or structurally confined by the dark material (Lucchitta, 1980; Parmentier and others, 1982; Shoemaker and others, 1982). The absence of demonstrated large lateral strike-slip displacements (Lucchitta, 1980; Parmentier and others, 1982) and the concentricity of the ancient furrow system expressed on sections of Galileo and Marius Regiones (Schenk and McKinnon, 1987) are evidence that the dark material has not been widely separated. Although dark-halo craters are not identified in Ganymede's polar regions, elsewhere on Ganymede they indicate that dark material has been excavated from shallow depths beneath the bright material (Schenk and McKinnon, 1985), thus providing further evidence that the dark material has not been widely spread apart. The existence of dark material at shallow depths beneath the bright lanes is not consistent with deep subsidence or stoping into the interior of blocks of dark material. It is consistent with the formation of bright material by rifting and filling where, in relatively narrow linear zones, relatively clean ice was emplaced over down-dropped blocks of dark cratered material.

The grooves are generally considered to be the result of extensional tectonics (McKinnon and Parmentier, 1986; Squyres and Croft, 1986). Single grooves are probably tension cracks or narrow grabens (Shoemaker and others, 1982; Squyres, 1982); pairs of grooves are interpreted as viscously relaxed grabens (Parmentier and others, 1982). Groove sets could be sets of tension cracks or sets of horsts and grabens. Grooves may be the surface expression of fractures in the underlying dark material, or they may develop solely at shallow depth due to continuing extension of the bright material (Murchie and others, 1986). They may have formed as a result of necking instabilities in a brittle layer overlying a more ductile substrate, as the strength of ice is strongly temperature dependent (Fink and Fletcher, 1981; Herrick and Stevenson, 1990). The different orientations of the groove sets are probably related to sequential episodes of bright-material emplacement (Golombek and Allison, 1981), possibly reflecting different stress systems.

The stress sources responsible for grooved material were probably some combination of global expansion due to continued internal differentiation (Squyres, 1980) and superposed regional and local stress fields (McKinnon, 1981; Parmentier and others, 1982; Zuber and Parmentier, 1984; Grimm and Squyres, 1985). A plausible regional stress source is convective upwelling; a plausible local source is the cooling of emplaced bright material. The response of Ganymede's lithosphere to these stresses was not spatially uniform. Within the map region a dominant extensional stress direction is oriented along the 190° meridian. Younger bright lanes near the crater Isis have a variety of orientations, suggesting a more isotropic extensional stress field.

GEOLOGIC HISTORY

No record of the early high impactor flux (Shoemaker and Wolfe, 1982) is preserved in the Hathor region. Early craters and basins were lost by extensive resurfacing and topographic relaxation. Only small polygons of densely cratered material remain, and these areas are characterized by small craters that probably do not reflect the initial period of cratering. The surface appears to have been been extensively modified by endogenous processes. Dominant were extensional tectonics and accompanying water-ice volcanism. The old, dark materials were extensively fractured by normal faulting, and as blocks of the dark material were down-dropped as grabens, they were nearly completely covered by brighter, cleaner ice from beneath. The mottled plains unit was probably emplaced at this time. Grooves in the bright materials then apparently formed over a long period, as superposed crater densities on the grooved materials differ considerably. Craters were not generally preserved until after the major period of groove formation. The palimpsests formed during this period, but the Gilgamesh multiring basin formed after it. Late-stage eruptions of smooth material resurfaced and partly flooded other units, but disruption of smooth material by groove formation was minor. Last emplaced were young, bright, sharp-rimmed craters.

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GEOLOGIC MAP OF THE HATHOR REGION (Jg–15) OF GANYMEDE

By

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